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Physical robustness of canopy temperature models for crop heat stress simulation across environments and production conditions

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ABSTRACT

Despite widespread application in studying climate change impacts, most crop models ignore complex interactions among air temperature, crop and soil water status, CO_2 concentration and atmospheric conditions that influence crop canopy temperature. The current study extended previous studies by evaluating T_c simulations from nine crop models at six locations across environmental and production conditions. Each crop model implemented one of an empirical (EMP), an energy balance assuming neutral stability (EBN) or an energy balance correcting for atmospheric stability conditions (EBSC) approach to simulate T_c. Model performance in predicting T_c was evaluated for two experiments in continental North America with various water, nitrogen and CO2 treatments. An empirical model fit to one dataset had the best performance, followed by the EBSC models. Stability conditions explained much of the differences between modeling approaches. More accurate simulation of heat stress will likely require use of energy balance approaches that consider atmospheric stability conditions.

1. Introduction

As temperatures warm with climate change, reductions in crop yields due to heat stress (Porter and Gawith, 1999; Wheeler et al., 2000) are expected to increase (Porter et al., 2014). Statistical models of crop yield response to weather have detected large yield declines across many regions as the number of days with extremely high temperature have increased (Lobell et al., 2011; Hawkins et al., 2013; Lobell et al., 2013; Hatfield, 2016). Heat stress depends on unique combinations of the timing and duration of high temperature events, crop phenological stage and varietal characteristics (Rezaei et al., 2015; Prasad et al., 2017), suggesting that process-based crop models may provide valuable insights into how high temperatures impact crop performance under climate change (White et al., 2011). It is only recently that process-based crop models have included heat stress effects on grain number, grain yield or crop senescence (Challinor et al., 2005; Asseng et al., 2011; Moriondo

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et al., 2011; Maiorano et al., 2017), with limited evaluation of their performance under heat stress conditions (Stratonovitch and Semenov, 2015; Gabaldón-Leal et al., 2016). Further, unlike their statistical counterparts, most process-based crop models do not account directly for the interaction of crop water status and high temperature events (Lobell and Asseng, 2017), although such interactions affect the magnitude of heat stress (Gourdji et al., 2013; Anderson et al., 2015; Troy et al., 2015). Recent efforts have estimated and evaluated canopy temperature (T_c) simulations in process-based crop models (Webber et al., 2016b; Webber et al., 2017), though with their evaluation limited to irrigated production in arid conditions. Canopy temperature has long been considered in irrigation scheduling (Jackson et al., 1977) and is used as a selection trait for drought and heat tolerance (Blum et al., 1982; Hatfield et al., 1987; Blum et al., 1989; Reynolds and Langridge, 2016). Typically, crops with cooler canopies maintain higher yields under water deficits or with heat stress under irrigated conditions (Blum et al., 1982; Blum et al., 1989; Olivares-Villegas et al., 2007; Lopes and Reynolds, 2010; Pinto and Reynolds, 2015), while Pinter et al. (1990) offer a slightly different interpretation.

The canopy temperature of crops generally follows ambient air temperature (T_{air}) but can drop below or rise above T_{air} due to the balance of radiative heating and transpirational cooling. The difference between T_c and T_{air}, termed canopy temperature depression ($\Delta T = T_c - T_{air}$) is larger and more negative with ample soil water supply and high vapor pressure deficit (VPD) (Idso et al., 1981; Jackson et al., 1981). Any factor which reduces the rate of transpiration, such as soil water deficit (Idso et al., 1981), low reference crop evapotranspiration (ET_o), typically driven by low VPD, or elevated atmospheric CO_2 concentrations (Kimball et al., 1999; Wall et al., 2000; Leakey et al., 2006; Wall et al., 2006; Gray et al., 2016) will reduce canopy cooling. When transpiration is restricted, T_c frequently exceeds T_{air} (Siebert et al., 2014).

Despite the importance of T_c for irrigation management and crop breeding, the complexity of calculations of T_c has likely discouraged wider application of T_c in crop models. Canopy temperature results from the energy balance at the crop surface, in which energy fluxes include net radiation, sensible and latent heat transfer as well as energy transfer with soils (Jackson et al., 1981). Beyond the complexity of stomatal regulation of gas exchange and its role in determining latent energy flux together with atmospheric evaporative demand (Jarvis and McNaughton, 1986), the stability of the air influences aerodynamic resistance, r_a, of the transfer of heat and vapor between the crop surface and the atmosphere (Monteith and Unsworth, 2007). For example, under stable atmospheric conditions, air near the canopy is heavier than the overlaying air such that buoyancy is inhibited and the aerodynamic resistance to heat and vapor transfer are relatively greater, whereas in unstable conditions, buoyancy of the air near the crop canopy reduces r_a (Monteith and Unsworth, 2007). The Monin-Obukhov Similarity Theory (MOST) is a common approach to determine r_a in which stability correction factors (Thom, 1975) are applied to logarithmic momentum, temperature and vapor fluxes (Monin and Obukhov, 1954), and consistitutes the main approach to energy balance correcting for atmospheric stability conditions (EBSC). However, stability corrections depend on T_c among other factors (Webb, 1970), implying that a solution of T_c using an EBSC approach requires an iterative solution (Liu et al., 2007). Two main alternatives avoid the complexity of correcting for boundary layer stability. The first assumes neutral stability conditions and solves a relatively straightforward energy balance (EBN) (Clawson et al., 1989), though the method implicitly assumes that T_c is close to T_{air}. The second option avoids an energy balance by using an empirical relationship (EMP) to relate T_c to main drivers, such as T_{air}, VPD and soil water status. The EMP methods have produced estimates of T_c similar to those of the EBSC methods for r_a (Liu et al., 2007) and T_c (Webber et al., 2017), but both studies noted that their results needed to be validated across a wider range of climates and growing conditions.

The main objective of this study was to assess the skill of different crop models in simulating T_c for a wide range of environmental conditions (locations, years, atmospheric CO_2 concentrations) and agronomic conditions (irrigated and rainfed, high and low nitrogen fertilization levels), extending a previous study which considered only potential production conditions under ambient CO_2 at one location. A second objective was to understand possible strengths of the different approaches for modeling T_c. The study is undertaken as part of the overall efforts of the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2013) Wheat group (http://www.agmip.org/wheat/) to understand the impacts of high temperature on wheat yields.

2. Materials and methods

2.1. Site and field experiment descriptions

Data from two series of experiments, here referred to as "FACE-Maricopa" and "China Wheat" were used to evaluate T_c simulations (Fig. 1). In the FACE-Maricopa dataset, a spring wheat (*Triticium aestivum* L.) cultivar was grown over four seasons with buried drip

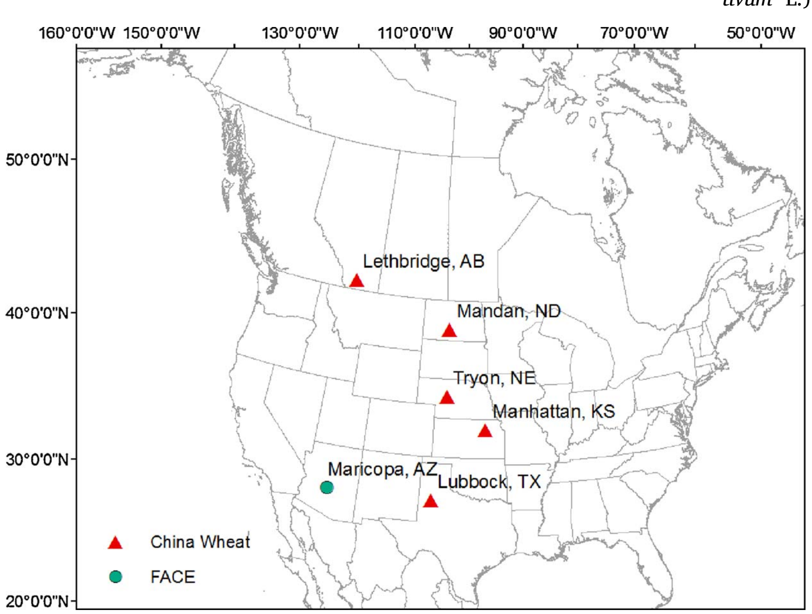

Fig. 1. Location of the FACE-Maricopa experiment and the five sites of the China Wheat experiment considered in this study.